

# Lifetime measurement of the $5d^2D_{5/2}$ state in $Ba^+$

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**Abstract** The lifetime of the metastable  $5d^2D_{5/2}$  state has been measured for a single trapped  $Ba^+$  ion in a Paul trap in Ultra High Vacuum (UHV) in the  $10^{-10}$  mbar pressure range. A total of 5046 individual periods when the ion was shelved in this state have been recorded. A preliminary value  $\tau_{D_{5/2}} = 26.4(1.7)$  s is obtained through extrapolation to zero residual gas pressure.

**Keywords** Single ion spectroscopy · electron shelving · atomic lifetime.

## 1 Introduction

The accurate determination of the transition probability of transitions in heavy alkali earth systems is an important step in the research program to measure Atomic Parity Violation (APV) in such systems [1, 2, 3, 4, 5, 6, 7, 8, 9]. In the research reported here, a single trapped  $Ba^+$  ion has been investigated and the lifetime of its  $5d^2D_{5/2}$  state has been measured. This provides essential input for testing atomic structure and, in particular, the atomic wavefunctions of the involved states at percent level accuracy. Such measurements are highly sensitive to variations of parameters that determine the experiment's performance during long periods (i.e. several hours) and which may cause systematic uncertainties. In particular, such effects may arise from interactions of the ion with background gas.

There are two main reasons for choosing single trapped  $Ba^+$  ion in UHV to perform precise lifetime measurements. Firstly, Barium (Ba) is a heavy alkaline earth metal. The  $Ba^+$  ion has a rather simple electronic configuration.

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Precise measurements provide for accurate tests of the atomic wavefunctions. Secondly, systematic errors due to collisions with other particles (such as different species) are highly suppressed.

The lifetime of the metastable  $5d^2D_{5/2}$  state in  $Ba^+$  has been measured earlier in different experiments [10, 11, 12, 13, 14, 15, 16]. Calculations are presently performed by different independent theory groups [5, 6, 17, 18, 19, 20, 21]. All the measurements to date as well as calculated values for the lifetime of  $5d^2D_{5/2}$  state in  $Ba^+$  have been compiled in Table 1.

Table 1: Calculations and measurements of the lifetime of the  $5d^2D_{5/2}$  state in  $Ba^+$  (see also Fig. 6). Note, some of the values have been reported without error bars.

Theory			Experiments		
Value[s]	Year	Reference	Value[s]	Year	Reference
29.8(3)	2012	[5, 6]	31.2(0.9)	2014	[15]
30.3(4)	2008	[19]	32.0(2.9)	2007	[13]
30.8	2007	[21]	32.3	1997	[16]
31.6	2007	[14]	34.5(3.5)	1990	[11]
30.3	2001	[18]	32(5)	1986	[10]
37.2	1991	[20]	47(16)	1980	[12]

## 2 Experimental setup

The trap for  $Ba^+$  in this experiment is a hyperbolic Paul trap [22]. It consists of a ring electrode and two end caps made of copper. The electrodes are mounted on a Macor holder. The chosen geometry results in a harmonic pseudopotential at the center of the trap when AC voltages are applied between the ring and the two endcaps. The latter are grounded. The operating RF frequency for the trap is  $\Omega_{RF} = 5.44$  MHz. The trap with its Macor holder is mounted on Oxygen Free High Conductivity (OFHC) copper base plate. In order to trap ions, there is a Ba oven (0.9 mm diameter  $\times$  40 mm length resistively heated stainless steel tube) which contains a mixture of  $BaCO_3$  and Zr. This oven produces a flux of order of  $10^6$  thermal Ba atoms/s. A laser at wavelength 413 nm is used to produce  $Ba^+$  ions in the trap by two-photon photoionisation. We use laser light at  $\lambda_1 = 493$  nm (frequency doubled from a Coherent MBR-110 Ti:Sa laser) for driving the  $6s^2S_{1/2}$ - $6p^2P_{1/2}$  cooling transition and laser light at  $\lambda_2 = 649$  nm (produced from Coherent CR-699 ring dye laser) for the  $6p^2P_{1/2}$ - $5d^2D_{3/2}$  repump transition (see Fig. 2). In the experiments reported here, the power of  $\lambda_1$  is between 6  $\mu$ W and 50  $\mu$ W and that of  $\lambda_2$  is between 6  $\mu$ W and 45  $\mu$ W. The Gaussian radius of the laser beams is about 60  $\mu$ m at the position of the ion for all the measurements. Fluorescence from the  $6s^2S_{1/2}$ - $6p^2P_{1/2}$  transition in the  $Ba^+$  ion is detected with a photomultiplier tube (PMT) and an EMCCD camera. Fig. 1 shows our hyperbolic Paul trap together with the image of ions that are trapped and localized at the potential minimum of the trap.

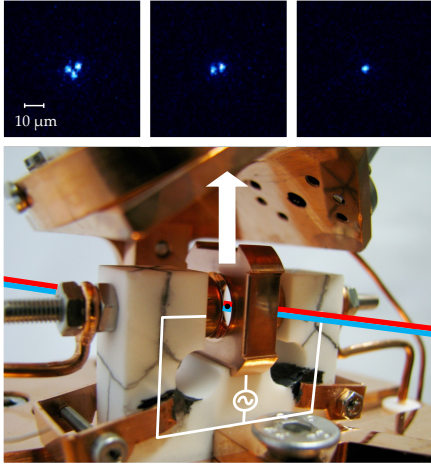


Fig. 1: Hyperbolic Paul trap of  $Ba^+$  ion. On top, images of 3, 2 and 1 ion are given.

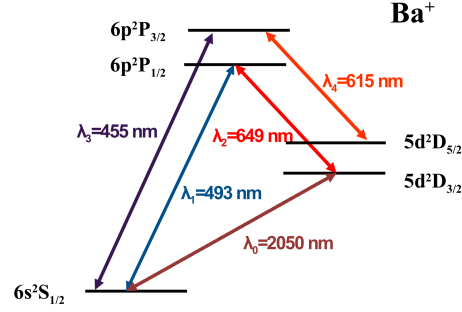


Fig. 2: Level scheme of  $Ba^+$  ion. The lowest  $^2S_{1/2}$ ,  $^2P_{1/2}$  and  $^2D_{3/2}$  electronic states form a closed three level system.

### 3 Electron shelving technique

$Ba^+$  ions have a closed three-level system. One of the excited states, the  $5d^2D_{5/2}$  state, is long-lived (see Fig. 2). Simultaneous laser radiation at  $\lambda_1$  and  $\lambda_2$  is therefore needed to cool the ion in the center of the trap. When the ion is exposed to the light of two laser beams at wavelengths  $\lambda_1$  and  $\lambda_2$  (see Fig. 2), there is a closed cycle of  $6s^2S_{1/2}$ - $6p^2P_{1/2}$ - $5d^2D_{3/2}$  transitions. Observing the fluorescence from the  $6p^2P_{1/2}$ - $6s^2S_{1/2}$  transition implies that the ion is “not shelved” in the  $5d^2D_{5/2}$  state. The electron shelving technique is employed in our experiment to determine the lifetime of the  $5d^2D_{5/2}$  state. With an additional fiber-coupled high power LED (M455F1) at  $\lambda_3 = 455$  nm wavelength the ion can be “shelved” to the  $5d^2D_{5/2}$  state via excitation to the  $6p^2P_{3/2}$  state and this state’s subsequent decay. The direct observation of “quantum jumps” in a single  $Ba^+$  ion between the  $5d^2D_{5/2}$  and  $6s^2S_{1/2}$  states has been first demonstrated by Nagourney et al. [10]. The decay of the  $6p^2P_{3/2}$  state is the start of a shelving period which ends with a quantum jump from the  $5d^2D_{5/2}$  state to  $6s^2S_{1/2}$  state. Fig. 3 displays the highest PMT count rate (2200cnts/s) when the ion is not shelved and the lowest count rate (600cnts/s) as background when it is shelved to the metastable  $5d^2D_{5/2}$  state. The “on/off” and “off/on” transitions in the fluorescence signal corresponds to the start and end of one single interval, when the ion was in the  $5d^2D_{5/2}$  state.

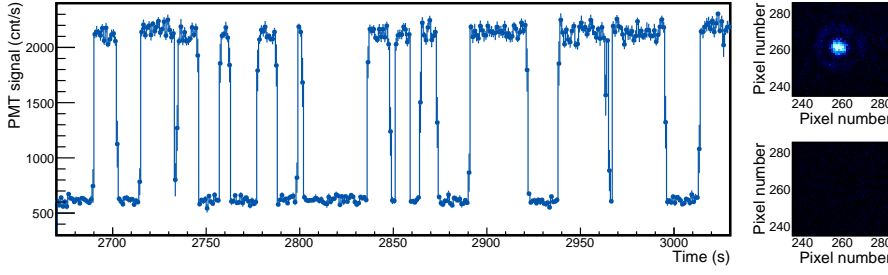


Fig. 3: Quantum Jumps observed in single  $\text{Ba}^+$  ion. Left : PMT count rate as a function of time. Right: EMCCD image of the ion in the unshelved state(top) and shelved state(bottom).

#### 4 Measurements

In order to measure the lifetime  $\tau_{D_{5/2}}$ , a total of 5046 individual shelved periods have been recorded in 71 data samples and analysed. They were taken under in part significantly different conditions to enable observing and correcting for systematic errors [23]. Fig. 4 represents one example of the analysed samples. It shows an exponential decay. Such a decay function is fitted to each data set using a binned log-likelihood method. The lifetime  $\tau_{D_{5/2}}$  is obtained for each data sample from the corresponding fit parameters. We note that experimental situations can be created where ion heating results in longer measured durations of individual dark periods than the actual dwell time of the ion in the  $D_{5/2}$  state. This can be seen in the slow recovery of the fluorescence light. Collisions with background gas can reduce the lifetime of the metastable state.

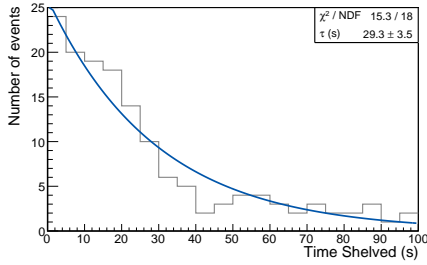


Fig. 4: One sample of the lifetime measurements in single  $\text{Ba}^+$  ion with 96 shelved periods.

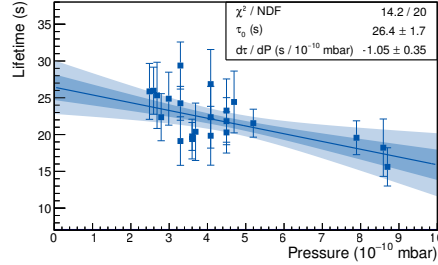


Fig. 5: Lifetime of the  $5d^2D_{5/2}$  state versus residual gas pressure in a single  $\text{Ba}^+$  ion. 68% and 95% confidence intervals are given.

In order to extrapolate the absolute value for the lifetime to zero pressure, the lifetime  $\tau_{D_{5/2}}$  was measured at different background pressures. Fig. 5 displays

the results for a selection of 1600 out of 5046 shelved periods. The uncertainty for the lifetime in each value corresponds to the statistical error from fitting an exponential decay to the data. A range of pressures between  $2.5 \times 10^{-10}$  and  $8.7 \times 10^{-10}$  mbar was explored by changing the temperature of the vacuum chamber in the range from 289 K to 296 K and by adjusting the pumping speed of the ion pump. For the small change in temperature needed here, changes in the collision cross-sections between the ion and the residual gas atoms can be neglected. A linear function is fitted to the data. The lifetime of the  $5d^2D_{5/2}$  state is found to be  $\tau_{D_{5/2}} = 26.4(1.7)$  s. 3446 shelved periods are used to check for systematics, such as potentially arising from laser intensities, laser frequency detunings, rf voltages for trap and effects from the operating conditions of the ion pump. No significant effects have been observed.

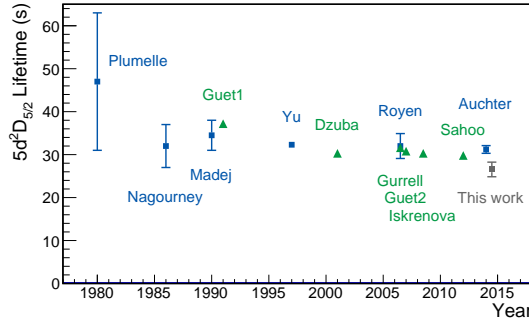


Fig. 6: Lifetime of the  $5d^2D_{5/2}$  state in a single  $Ba^+$  ion versus time within the last four decades. Squares represent measurements and triangles represent calculated values. Note, the result Guert2 [21] differs from Guert1 [20] by an omitted term.

## 5 Conclusions

In summary, the lifetime of the metastable  $5d^2D_{5/2}$  has been measured for a single  $Ba^+$  ion. The measured value is preliminary because cross checks for systematics are still ongoing. Our result agrees within  $2\sigma$  with the most recent theoretical value  $\tau_{D_{5/2}} = 29.8(3)$  s [6] and with the latest independent experimental value of  $\tau_{D_{5/2}} = 31.2(9)$  s [15]. Fig. 6 displays the time evolution of the measurements and the theory values for the lifetime of the  $5d^2D_{5/2}$  state in a  $Ba^+$  ion.

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